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No-till is more of sustaining the soil than a climate change mitigation option

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ABSTRACT

No-till is often referred to as a climate change mitigation option, possibly with a stronger conviction, than as a practice to manage soil organic C (SOC) content. We conducted a global meta-analysis to evaluate the effect of no-till (NT) on SOC concentration (SOC_c, g C kg^{-1} soil) and stock (SOC_s, Mg C ha^{-1} land) across climate, soil texture, cropping systems, and no-till duration to appraise the priority-setting. Compared to conventional tillage, NT favoured a significant rise (ΔSOC_c) of 38% in the 0–5 cm soil layer and a much lesser 6% increase in the 5–10 cm layer and no change beyond 10 cm. The temperate climate had nearly twice ΔSOC_c in the 0–5 cm layer compared to other climates, while the tropical climate favoured sub-surface accumulation. Coarse- and medium-textured soils and the inclusion of legumes in crop rotation facilitated larger positive ΔSOC_s under NT. The microbial biomass C was the most abundant C pool, with 61% and 23% increases under NT in 0–5 and 5–10 cm layers. A large ΔSOC_c in aggregates also characterized the top 0–5 cm layer. The difference in SOC_s was realized to a maximum 30 cm depth (5.4 Mg ha^{-1} or 14%) in favour of NT, although varying with the duration of its adoption. The contribution of NT in mitigating global anthropogenic greenhouse gas emissions is meagre, although it can substantially offset emissions from agriculture (17–58%). The benefit of NT in improving SOC is primarily restricted to the surface layer, which is potentially exposed, and therefore an increase could be short-lived. Nevertheless, a short-term gain in SOC is likely to enhance soil quality and crop productivity. Thus, NT may be promoted as a sustainable agricultural management practice rather than emphasizing its role as a potential climate change mitigation option.

1. Introduction

Globally, the soil holds about 1500 Pg (1 Pg = 10^{15} g) of organic C (SOC) in the upper one-meter soil layer (FAO, 2017). It is twice as much as the atmospheric CO_2 pool and thrice of the biotic pool (Lal, 2010; IPCC, 2013) and therefore plays a significant role in balancing the global C cycle. No-till (NT) with crop residue retention has been widely reported as a key option to increase soil C storage (Virto et al., 2012; Corbeels et al., 2016; Francaviglia et al., 2017), although there are reports of no change (e.g., Carter, 2005; Dimassi et al., 2014; de Sant-Anna et al., 2017). Increases are conspicuous mainly in the upper soil layer (10 cm or less), and it is essential to consider the whole soil profile for comparison with conventional tillage practice (Angers and Eriksen-Hamel, 2008; Mondal et al., 2020).

The change in SOC in the top layer(s) brings significant differences in soil properties, which may lead to improved crop growth (Powlson et al., 2014). However, the increases in SOC are soil- and climate-specific, and the role of no-tillage for climate mitigation has been controversial (Ogle et al., 2019). Moreover, the effect of NT on SOC is restricted to the top soil layers, while conventional tillage may increase SOC in deeper layers (e.g., Angers and Eriksen-Hamel, 2008; Luo et al., 2010). For various reasons, soils in many regions are tilled intermittently but referred to as NT, thus unleashing the accumulated SOC over the periods (Powlson et al., 2014).

Global analyses to evaluate the impact of NT on SOC have primarily focused on the upper 30 cm of the soil profile (West and Post, 2002;

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Alvarez, 2005; Angers and Eriksen-Hamel, 2008; González-Sánchez et al., 2012; Virto et al., 2012; Aguilera et al., 2013). Although this may explain the role of NT in sustaining agricultural productivity, it fails to consider its role in C sequestration (20–50 years of change, Burras et al., 2001) and climate change mitigation. Studies that evaluated deeper soil depths (>30 cm) reported a highly variable response of no-till ranging from no change (VandenBygaart et al., 2003; Luo et al., 2010) to significant (Angers and Eriksen-Hamel, 2008; Álvaro-Fuentes et al., 2008; Govaerts et al., 2009; Christopher et al., 2009) changes of SOC. Moreover, change in SOC stock under diverse climate, soil condition, and management practices at a global scale have sparsely been reported (e.g., Ogle et al., 2019).

The stabilization of SOC is related to soil aggregate dynamics. Soil micro-aggregates protect the SOC in the long run, while macro-aggregates turnover is crucial for its stabilization (Six et al., 2004). Other pools of SOC- the particulate organic matter-C (in fresh and decomposing residues with widely variable turnover time) and the microbial biomass C (of bacteria and fungi with a rapid turnover time) are affected by tillage and are indicative of SOC sequestration potential in NT soils.

We hypothesize that (1) NT brings a significant change in SOC concentration (SOC_c g C kg^{-1} or %) in the topsoil and a small or no difference in the subsoil compared to the conventional tillage; (2) the C is preferentially located in the labile pools; (3) the change in SOC stock (SOC_s, Mg C ha^{-1}) by NT is limited to a small segment of the soil profile, with an inconsequential contribution to greenhouse gases (GHGs) mitigation potential. To test the above hypotheses, a global meta-analysis was performed with 5850 paired data points (2294 and 3134 pairs for SOC_c and SOC_s, respectively) collected from 546 peer-reviewed published literature. Data were also analysed for changes across climates, soils, crop rotations, and duration of NT cultivation.

2. Materials and Methods

2.1. Search of data

Peer-reviewed publications (2000–2017) were searched for the effects of no-till compared to conventional tillage practice (CT; here 'control') by using the Web of Science (Elsevier) indexing service, with keywords "tillage' AND 'soil'' in the article abstract. The parameters were: (a) SOC concentration (SOC_c, g C kg^{-1} of soil), (b) SOC stock (SOC_s, Mg C ha^{-1} of land), (c) SOC_c pool (microbial biomass C, MBC; macro-, meso-, micro-and silt+clay size aggregate-associated C, C_{MaA}, C_{MeA}, C_{MiA}, C_{S+C}, respectively; and (d) particulate organic matter-C, POM-C; all in g C kg^{-1} of soil). Conference proceedings and non-English language publications were excluded. Studies were selected exclusively based on the following criteria:

1. Field experiments included a one-to-one comparison between NT and CT practices.
2. In studies with more than one CT practice, 'CT' was identified as the treatment with the most extensive tillage-induced soil disturbance.
3. It was no-till, with residue retained on the surface as mulch in all cases.
4. Where fertilizers or soil amendments were applied at variable rates in a study, no-till and CT were chosen with similar quantities.
6. Studies with a minimum of three years of continuity were selected.

The locations of studies used in the analysis are indicated on a global map (Supplementary Fig. S1**)**, and their listing is given in detail in Supplementary Table S1.

2.2. Database preparation

The average values of parameters listed above in each soil layer under NT and CT were collected from each study. The SOC_c was grouped into the following soil layers: 0–5, 5–10, 10–20, 20–30, and > 30 cm. In studies with layers other than the above, these were reclassified to the nearest groups with a 3-cm overlapping of group boundaries (Mondal et al., 2020). The SOC_s were categorized into 0–5, 0–10, 0–20, 0–30, 0–50, and 0–100 cm layer segments, as reported in studies. This resulted in independent datasets of SOC_c (layer increments) and SOC_s (layer segments). Data reported in figures (not in tables) in published literature were extracted using WebPlotDigitizer ver. 3.12 (Rohatgi, 2016).

Categorical variables like latitude-longitude of study location (Lat-Lon), duration of NT experimentation (Duration), crop rotation (Rotation), and soil texture (Texture) were recorded from each study. Google Maps (maps.google.com) was used to extract a place's coordinates if a study's Lat-Lon data was unavailable. The R-package "kgc" was used for identifying climatic zones (Climate; tropical, continental, dry, and temperate; Köppen-Zeiger climatic classification) from the Lat-Lon information (Rubel et al., 2017). Annual rainfall (mm) and annual average temperature (°C) of a location were obtained from the "worldclim" database using the "raster" package in R statistical platform. In studies where soil textural classes were not mentioned, the same was determined using the texture triangle (NRCS USDA Texture Calculator, www.nrcs.usda.gov) from sand-silt-clay information. Textural classes were regrouped into three: fine- (sandy clay, silty clay, and clay), medium- (silty clay loam, clay loam, silt, silty loam, and loam), and coarse- (sandy loam, sandy clay loam, loamy sand, and sand) textured soils. Crop rotations were broadly classified into cereal-cereal (C-C), cereal-legume (C-L), cereals and non-legumes in rotation (C-O), legume-legume in rotation (L-L), and non-cereals and non-legumes in rotation (OTH). The 'Duration' was taken as the period between the initiation of the experiment and the reporting year if not indicated otherwise. The duration was classified into 1) $\le$ 10, 2) 10–20, and 3) > 20 yr. Climate and soil variables and the duration are summarized in Supplementary Table S2.

All studies used wet digestion or dry combustion method to measure the SOC_c. In the wet digestion method, SOC was chemically-oxidised and back-titrated to know the content, while in the dry combustion method, the weight loss due to the burning of SOC was measured. In all cases, inorganic C content in soil samples was either insignificant or removed before the analysis. Soil bulk density (BD) expressed as dry soil weight (g) per unit volume (cm^3) was determined by the core method. A known volume of soil was oven-dried, and dry weights were recorded. In studies (~8%) where SOC_s were not reported, SOC_c was converted to SOC_s by using the following formula (Mondal et al., 2019; Eq. 1):

$$SOCs\left(Mgha^{-1}\right) = SOCc \times BD \times \frac{L}{10} \tag{1}$$

where 'L' is the thickness of the soil layer (cm) [both L and BD were reported in the study].

Microbial biomass C (MBC) was determined by fumigation-extraction, substrate-induced respiration, or irradiation-extraction methods. Separation of particulate organic matter (POM) was performed by following the procedures of Cambardella and Elliott (1992). The C in aggregates and POM-C were determined either by wet digestion or dry combustion method.

2.3. Data analysis

The meta-analysis was carried out through the "metafor" package (Viechtbauer, 2010) in the R statistical computing platform (R Core Team, 2020). The natural log of the response ratio (ratio of NT and CT; LRR) was taken as the effect size of the study (Hedges et al., 1999; Eq. 2). Since the within-study variance of means of parameters was not available for most studies, individual observations were weighted by the experimental replications (Adams et al., 1997; Eq. 3). In situations where more than one observation from a study was included in a single category, weights were divided by the total number of observations recorded. The LRR was finally back-transformed to generate a percent change in the parameter (Eq. 4).

$$Effectsize = LRR = \ln\left[\frac{Mean_{NT}}{Mean_{CT}}\right] \tag{2}$$

$$Weight = \frac{N_{NT} \times N_{CT}}{N_{NT} + N_{CT}} \tag{3}$$

$$Percentchange = [\exp(LRR) - 1] * 100 \tag{4}$$

where Mean_{NT} and Mean_{CT} are means of parameters under no-tillage and conventional tillage, respectively; N is the number of replicates.

Effect sizes from all studies were combined using a random-effects model and considered significant ($p < 0.05$) if the 95% confidence intervals (CIs) did not overlap with zero. Meta-analysis was also performed for the categories (Climate, Texture, Rotation, and Duration). Publication bias was assessed through histograms (Rosenberg et al., 2000), and in none of the cases, effect sizes showed preferences toward either positive or negative bias (Supplementary Fig. S2).

Additionally, we performed the mixed model analysis with location as 'random' and others as 'fixed' factors to (a) substantiate the meta-analysis results and (b) to generate absolute values of C stock for C sequestration potential estimates (discussed below). The GLIMMIX procedure in SAS has been used for estimating the mixed model for the present dataset.

By and large, the meta- and mixed model analyses showed similar trends, and, therefore, primarily, the meta-analysis results are described in the main text. The mixed model results are given in the Supplementary Information. In the discussion, however, inferences were drawn from the meta-analysis and mixed model results together.

For the estimation of SOC sequestration potential of no-tillage, the change in SOCs (NT-CT, Mg C ha^{-1}) at different depth intervals was obtained from the mixed model analysis and divided by the duration of NT practice to quantify the C-sequestration rate (Mg C ha^{-1} yr^{-1}). The area under no-tillage (current and potential, Mha) was obtained from Prestele et al. (2018), and global C-sequestration potential was calculated as:

$$\begin{aligned} &GlobalC - sequestrationpotential\left(TgCha^{-1}yr^{-1}\right) \\ &\quad = C - sequestrationrate\left(MgCha^{-1}yr^{-1}\right) \times No - tillarea(Mha) \end{aligned} \tag{5}$$

3. Results

3.1. Impact of no-till on SOC concentration and stock

The meta-analysis showed a large increase (37.8%) in SOC_c in the 0–5 cm layer under NT. Compared to CT, the increase was only 6.2% in the 5–10 cm depth (Fig. 1**a**). The changes were marginal further down the soil depth, leading to an average of 8% increase over the 1-m soil profile. NT resulted in a large increase (33.6%) in SOC_s in the 0–5 cm layer, with more minor changes when the profile depth increased progressively (Fig. 1**b**). For a 1-m layer, the increase was only 5% under NT.

3.2. Changes in SOC concentration and stock in response to climate, soil texture, and cropping systems

In the 0–5 cm soil layer, the temperate climate had a 45.8% increase in SOC_c in NT compared to CT while other climatic zones had similar changes of 22–28% (Fig. 2**a**). The changes were identical among the climates down the profile. However, the impact of NT extended deeper in the profile in the tropics 5.9% and 4.4% increases in 20–30 and $>$ 30 cm layers, respectively). The impact of NT did not vary with soil texture (Fig. 2**b**). The change was in favour of NT up to 20 cm depth and no apparent changes thereafter. The C-C rotation had greater SOC_c change in the 0–5 cm layer compared to 31.6% in C-L in favour of NT but had similar changes in other crop rotations (Fig. 2**c**). However, C-L rotation facilitated greater SOC_c in NT in the 10–20 (11.3%) and 20–30 (17.1%) cm soil layers. With the increase in the duration, NT facilitated higher SOC_c in 0–5 and 5–10 cm layers (Fig. 2**d**). In the 0–5 cm layer, NT had 22.1%, 28.6%, and 38.2% higher SOC_c with $\leq$ 10, 11–20, and $>$ 20 yr of study, respectively. The NT's impact was visible in the 5–10 cm layer with longer durations (11–20 and >20 yr) but recorded no changes in other layers.

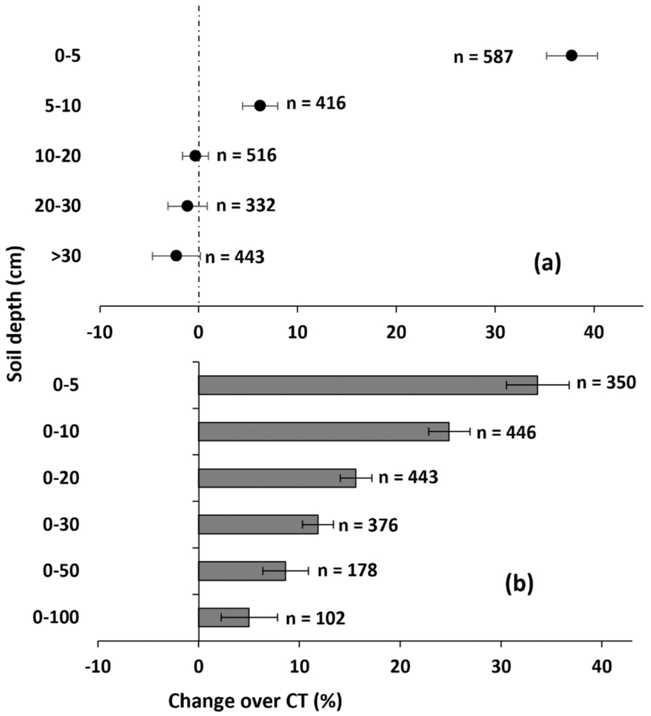

Fig. 1. Meta-analysis of soil organic C concentration (**a**) and stock (**b**) in different soil layers under no-till practice in comparison with conventional tillage (CT). [Horizontal bars indicate 95% confidence intervals for meta-analysis, and the standard error for the mixed model; 'n' is the number of data points for each soil layer].

No-till had varying effects on SOC_s among climates and soil types across different soil layers (Fig. 3**a&b**). The effect decreased as the profile depth e temperate climate showed more significant gains for 0–10 (41.5%), 0–20 (31.9%), and 0–30 (17.2%) cm profiles compared to dry (7.5–26.1%) and continental (6.8–16.0%) climates in these depths. The tropical climate had similar responses to other climates, except for the 0–10 cm profile, where it had lower accumulation under NT compared to the temperate climate. Beyond 50 cm, limited data were available to evaluate the impact of NT across climate types. Soil texture had no apparent effect on change in SOC_s in the top 0–5 cm layer. However, coarse- and medium-textured soils showed larger changes in favour of NT for 0–10 cm (29.4 & 26.2%), 0–20 cm (17.4 & 17.1%), and 0–30 cm (17.6 & 11.0%), compared to fine-textured soils (17.4, 10.7 & 8.9% in respective layers). The inclusion of legumes in rotation facilitated larger change for 0–20 (14.8%) or 0–30 (7.6%) cm profile (Fig. 3**c**). The effect of crop rotation was otherwise, not apparent. The increase in SOC_s was larger in the 0–5 over $\leq$ 10 and 11–20 yr, and in the 0–20 cm layer over $>$ 20 yr of NT duration (Fig. 3**d**). The response was similar considering other profile depths.

3.3. Change in SOC pools

The meta-analysis of microbial biomass-C (MBC) showed increases of 61.4% in the top 0–5 cm and 23.0% in the 5–10 cm layer (Table 1). The particulate organic matter-C (POM-C) had significant variations across depths, and the impact of NT was not evident. The SOC associated with macro-aggregates had 43.1% and 11.6% higher accumulation in favour of NT in 0–5 and 5–10 cm layers, respectively. NT resulted in 45.5%,

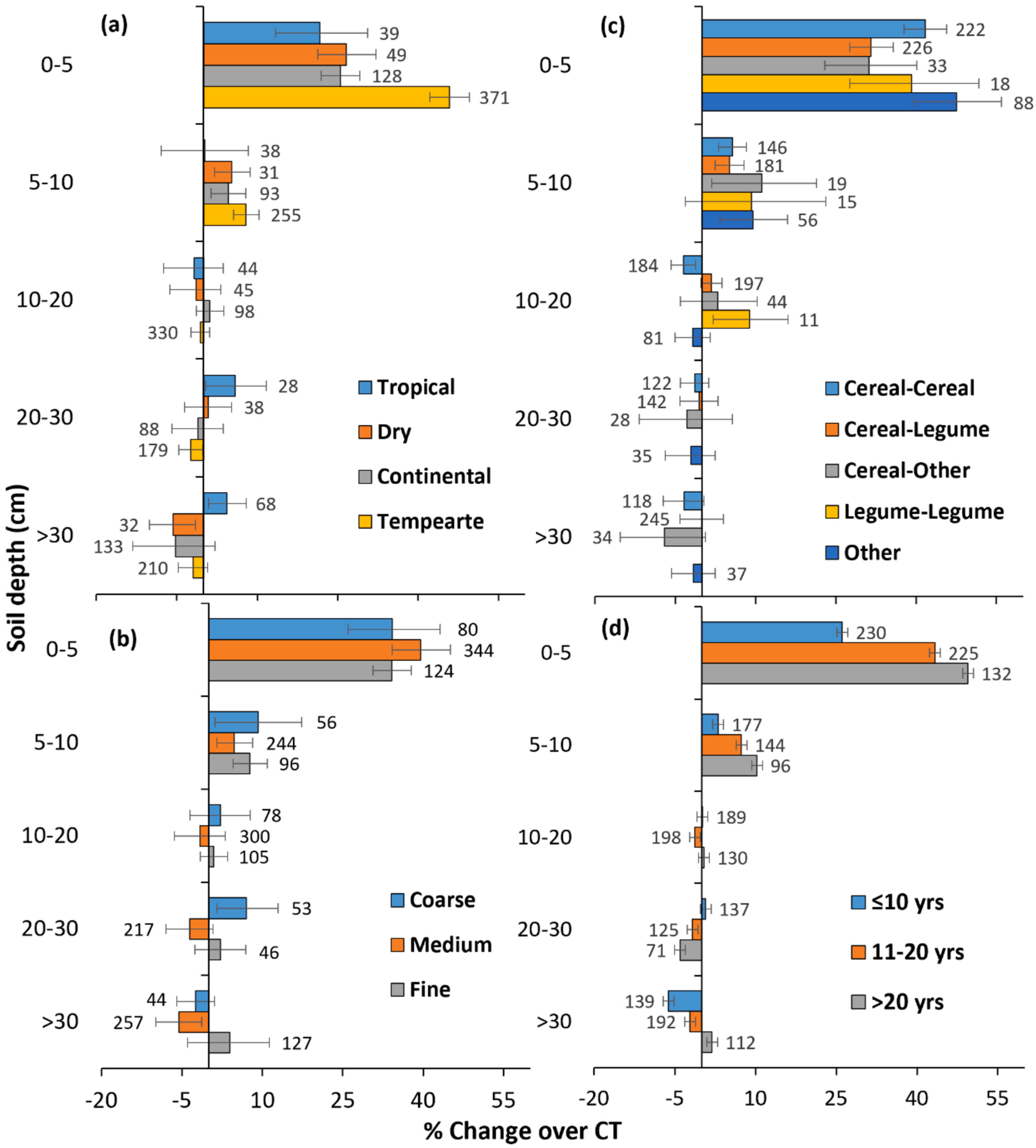

Fig. 2. Impact of climate (**a**), soil texture (**b**), cropping system (**c**), and experimental duration (**d**) on changes in SOC concentration (% of conventional tillage, CT) in different soil layers [95% confidence intervals are shown as horizontal bars, and significant if not cropping zero; 'n' = number of paired data points].

45.0%, and 23.2% increases of meso-, micro-, and silt+clay associated SOC in the 0–5 cm layer. No apparent changes were recorded in other soil layers.

3.4. Partial dependence of change in SOC stock with latitude, mean annual precipitation, mean annual temperature, clay content, and experimental duration

The change in SOC stock has been regulated substantially by climate, soil, and experimental period (Fig. 4). Although lower latitudes facilitated higher SOCs in NT, higher mean annual rainfall and temperature were more favourable for SOC in NT. The impact of NT is most apparent in soils with clay content at ~20% and decreased with an increase in clay content thereafter. The period of NT practice had a substantial impact on SOC stock but attained a near-equilibrium beyond 40 years.

3.5. Difference in SOC stock (0–30 cm soil profile) across climates, soil types, and cropping systems under NT

The mixed model analysis recorded an absolute maximum change in SOC_s (NT-CT) of 5.4 Mg C ha^{-1} in favour of NT, considering a 0–30 cm soil profile (Supplementary Fig. S3). It was similar for 0–50 or 0–100 cm soil profiles; therefore, 0–30 cm was taken as the ideal depth to realize impact instead of a longer profile. The difference (0–30 cm) was 4.75, 6.64, and 11.47 Mg C ha^{-1} over ≤ 10, 11–20, and > 20 yr of NT adoption (Table 2). Changes were similar between tropical (5.73 Mg C ha^{-1}) and temperate (5.51 Mg C ha^{-1}) climates for ≤ 10 yr but were greater compared to the continental (1.25 Mg C ha^{-1}) and dry (1.42 Mg C ha^{-1}) climates. However, with 11–20 yr of adoption, a larger accumulation under NT was recorded in the temperate climate (5.76 Mg C ha^{-1}) than in the continental or dry climates. Limited data for tropical climate (11–20 yr) and tropical and dry climates (>20 yr) did not allow further analysis. The impact of NT was higher in coarse- or fine-textured

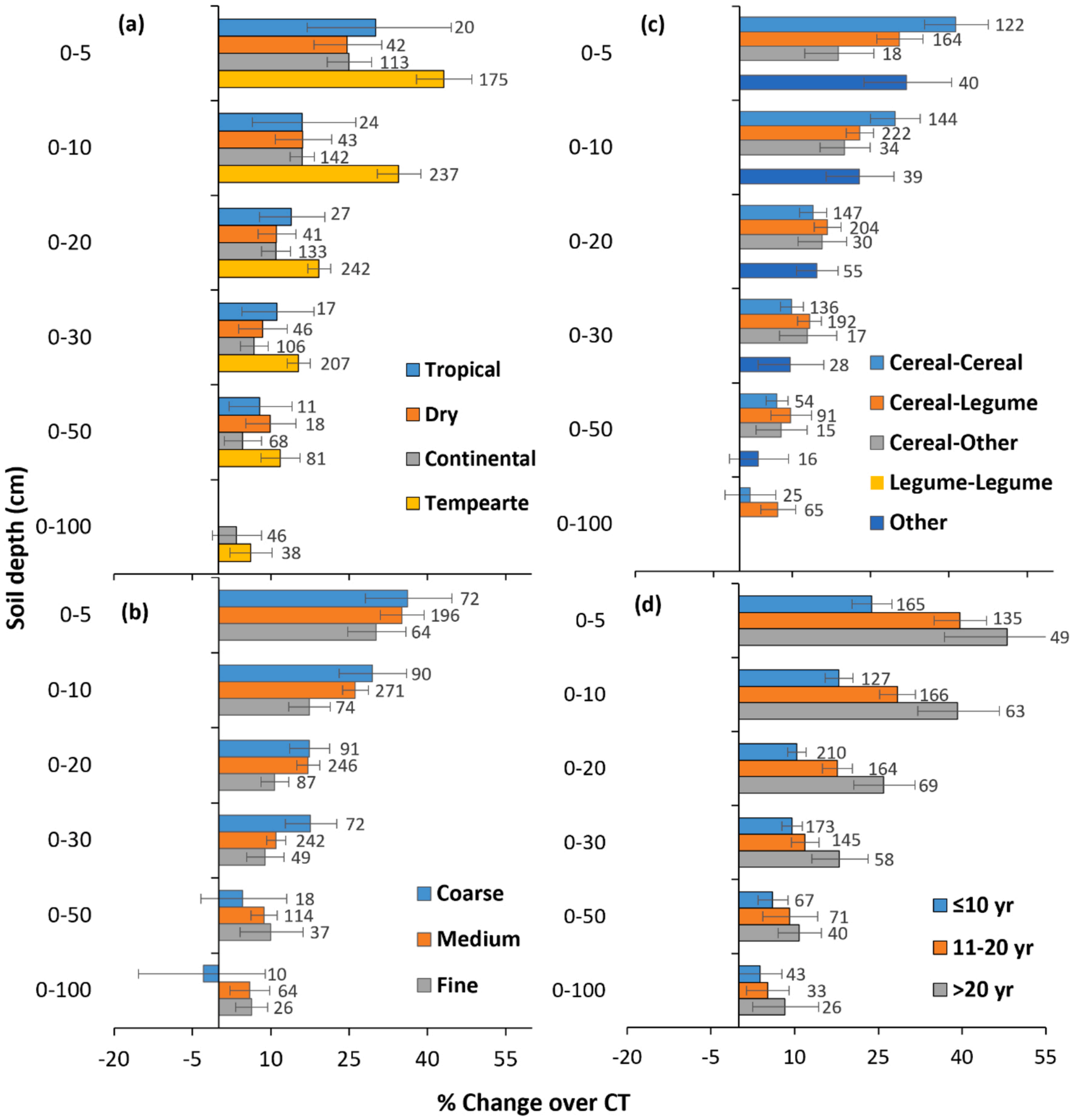

Fig. 3. Changes (% of conventional tillage, CT) in SOC stock in different soil layers in the no-tillage as influenced by climate (**a**), soil texture (**b**), cropping system (**c**), and experimental duration (**d**) [Error bars indicate 95% confidence intervals, and are significant if not crossing zero; 'n' = number of paired data points].

Table 1
Impact of no-till on the concentrations of soil organic C pools#.

Soil layer (cm)	N$	% Change over the conventional tillage	N	% Change over the conventional tillage
		Microbial biomass-C		*Particulate organic matter-C*
0–5	74	61.4 * *	32	51.1
5–10	56	23.0 * *	15	4.1
10–20	52	5.8	21	-2.5
> 20	33	12.9	20	0.1
		C in macro-aggregate		*C in meso-aggregate*
0–5	40	43.1 * *	42	45.5 * *
5–10	21	11.6 * *	22	0.9
10–20	19	-5.0	18	-5.5
> 20	16	-17.9	21	-15.1
		C in micro-aggregate		*C in silt+clay-sized aggregate*
0–5	48	45.0 * *	39	23.2 * *
5–10	28	2.7	22	-2.8
10–20	32	1.2	18	0.9
> 20	25	-7.0	20	1.2

#Microbial biomass C in mg kg-1; other pools are in g kg-1.
$N is the number of paired data

soils with ≤ 10 yr (6.44 and 5.17 Mg C ha^{-1}) and 11–20 yr (8.43 and 5.69 Mg C ha^{-1}) duration, while medium-textured soils were more effective at > 20 yr. The cereal-legume rotation was marginally favourable compared to the cereal-cereal system; for other crop rotations, results were inconclusive, or the data were limited.

3.6. Global C-sequestration potential of no-tillage and offsets for GHGs emissions

Globally, the area under no-till is estimated to be 158.3 Mha (Prestele et al., 2018; Table 3). Our estimate of C-sequestration potential in the global NT area is likely to be 250.7 Tg yr^{-1} higher than CT with ≤ 10 yr of uninterrupted NT practice. This reduces to 95.6 and 86.5 Tg yr^{-1} for 11–20 and > 20 yr of NT cultivation, respectively. However, the potential area under the no-till cultivation is estimated as 533 Mha (38% of global arable land), considering an integrated system of permanent NT, residue management, and crop rotations (Prestele et al., 2018; Table 3). Therefore, the global C sequestration potential of NT may increase to 291.1, 321.8, and 844.0 Tg yr^{-1} compared to CT over ≤ 10, 10–20, and > 20 yr of its duration.

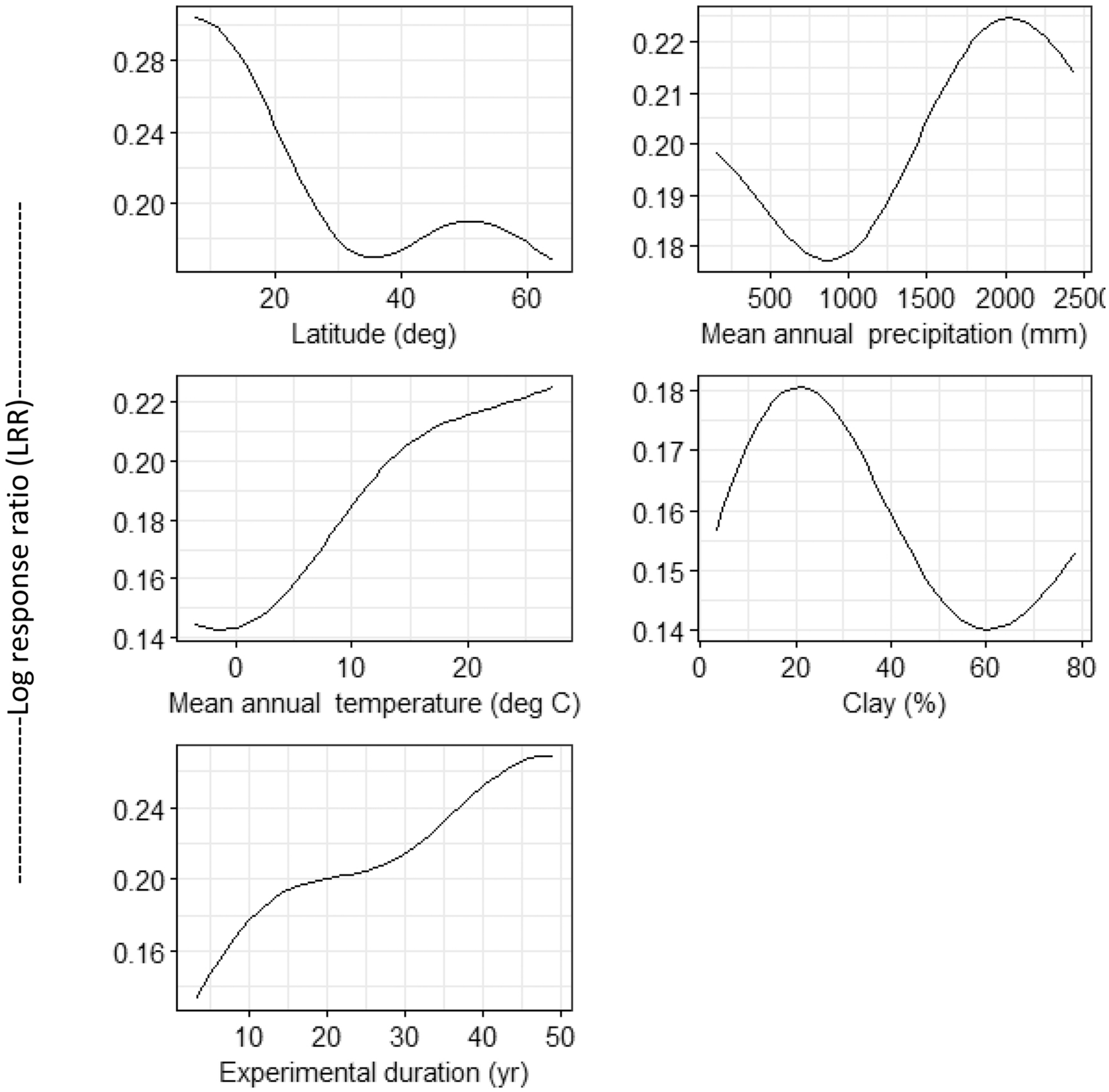

Fig. 4. Partial dependence of log response ratio (LRR) of SOC stock on latitude, mean annual precipitation and temperature, soil clay content, and experimental duration based on a support vector machine.

Table 2

Impact of no-till duration on SOC stock (0–30 cm) across climate, soil type, and cropping systems [values are mean of ΔSOC (no-till – conventional till) in Mg C ha^{-1} with standard error and numbers of paired data in parentheses].

	Duration		
	≤ 10 Years	11–20 Years	> 20 Years
Overall	4.75 **(1.23, 166)	6.64 **(1.76, 136)	11.47 **(3.06, 76)
Climate			
Tropical	5.73 **(1.92, 23)	-	-
Dry	1.42(0.99, 35)	4.16 **(1.29, 23)	-
Continental	1.25(2.41, 55)	4.36(2.90, 60)	10.53 * (5.04, 26)
Temperate	5.51 **(0.82, 127)	5.76 **(1.14, 122)	9.46 **(1.61, 40)
Soil Texture			
Coarse	6.44 **(1.06, 71)	8.43 *(3.45, 27)	-
Medium	2.44 *(1.04, 134)	4.62 **(0.84, 155)	11.44 **(2.99, 56)
Fine	5.17 **(1.49, 22)	5.69(2.79, 23)	7.89 **(2.20, 11)
Cropping system			
Cereal-Cereal	3.04 **(1.03, 98)	3.70 **(1.06, 69)	7.19 **(2.38, 13)
Cereal-Legume	4.75 **(1.23, 121)	6.65 **(1.76, 97)	10.70 **(2.94, 51)
Legume	-	-	-
Cereal-Other	-	7.78(7.38, 12)	-
Other	3.63 * (1.47, 12)	2.81(2.77, 15)	-

The GHGs emissions through crop & livestock activities are estimated at 5.3 Gt CO_2, and 4.0 Gt CO_2 coming through agricultural land use, making a total of 9.3 Gt CO_2 contribution from agriculture (FAO, 2020). With the current area estimates, adoption of NT may offset crop & livestock emissions by 17.3% yr^{-1} with $\leq$ 10 yr duration to 6.0% yr^{-1} with $>$ 20 yr period (Fig. 5). It may offset emissions from agricultural land use by 23.0%, 8.8% and 7.9% for $\leq$ 10, 11–20 and $>$ 20 yr duration. When the potential area under NT is considered, 20.1–58.4% and 26.7–77.4% of emissions from crop & livestock and agricultural land use could be counterbalanced. However, the contribution of NT in mitigating fossil fuel GHGs emissions will still be 3–9% only.

4. Discussion

Most changes in SOC happened within the top 5 cm soil, which is in close agreement with West and Post (2002), who reported C sequestration predominantly within the top 7 cm layer. We found that the most significant change in SOC stock under no-till was within 30 cm depth, similar to changes over 0–50 or 0–100 cm soil profile (Supplementary Fig. S3). Haddaway et al. (2017) reported no change beyond 30 cm depth. Although some studies suggested unequal redistribution of soil C under no-till, with a net gain in shallow depth and a net loss in deeper

Table 3
Global C-sequestration potential (ΔSOC, NT-CT; Tg C yr^{-1}) following ≤ 10, 11–20, and > 20 years of no-tillage adoption.

Continent	Current area[1]	Potential area[1]	ΔSOC (current area basis)			ΔSOC (potential area basis)		
			≤ 10 yr	11–20 yr	> 20 yr	≤ 10 yr	11–20 yr	> 20 yr
	……………… Mha………………		……………………………Tg C yr^{-1}………………………………					
Asia[2]	14.8 (11.1–18.5)	217.3	23.4	8.9	8.1	344.0	131.1	118.7
Europe[3]	4.1 (2.3–23.7)	67.6	6.5	2.5	2.2	107.1	40.8	36.9
Africa	1.2 (0.9–1.5)	29.6	1.9	0.7	0.7	46.9	17.9	16.2
North America	53.9 (45.1–72)	103.3	85.4	32.6	29.5	163.6	62.4	56.4
South America[4]	66.4 (50–77.1)	91.8	105.2	40.1	36.3	145.3	55.4	50.1
Oceania	17.9 (12.6–22.3)	23.5	28.3	10.8	9.8	37.1	14.2	12.8
Global	158.3 (122.1–215.2)	533.0	250.7	95.6	86.5	844.0	321.8	291.1

1After Prestele et al. (2018); [2]Includes Russia, [3]Includes Ukraine, and [4]Includes Mexico

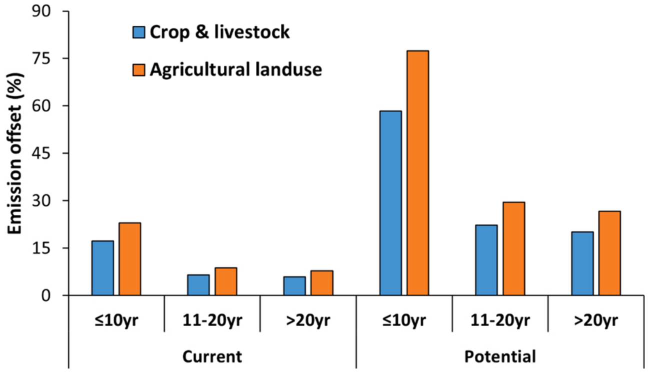

Fig. 5. Estimations of GHGs emissions offsets from agriculture through the adoption of no-tillage with durations in years [Current = Estimates with cultivated land currently under no-till; Potential = Estimates with current + other potential areas of no-till].

layers (Baker et al., 2007; Luo et al., 2010; Mondal et al., 2020), the average SOC stock in the soil profile was greater in NT than in CT (Angers and Eriksen-Hamel, 2008).

Climate fairly moderated the depth distribution of changes in SOC. The no-till impact is reduced under the prevailing hot and humid climate in the tropics in the top 0–5 cm layer compared to the temperate climate. However, there is an intriguing advantage of no-till in the tropical climate in the 20–30 and > 30 cm layers, which had a 4–6% increase in the SOC. Greater pore connectivity in NT (Talukder et al., 2022) might have induced mineralized C to move to deeper layers. The relative advantage of no-till improved in lower depths when rainfall and temperature increased (Supplementary Table S3**;** Fig. S4-S5), indicating that the tropical soils may have a higher potential for SOC accumulation under the no-till at lower depths. A similar change in the 15–30 cm soil layer was reported by Haddaway et al. (2017). Higher mean annual temperature and precipitation are the characteristics of a tropical climate, all of which favoured high SOC in NT (Fig. 4). A higher SOC in the upper layer of soil under the temperate climate is explained by a slower turnover of soil organic matter (Ayanaba and Jenkinson, 1990) and, therefore a higher mean residence time of C in the top layer (Trumbore, 1993). On the contrary, the impact of no-till in the surface layer(s) may be short-lived in the tropical climate. It has large variabilities, possibly due to the variation in input management practices (e.g., irrigation and fertilizer scheduling). The effect of climate on SOC stock has been inconclusive in a global analysis (Meurer et al., 2018), possibly due to more significant impacts of local rainfall and temperature conditions, the duration of the no-till practice (Luo et al., 2010), or other factors at the agroecosystem level (Virto et al., 2012). Increasing mean annual temperature hastens C mineralization (Conant et al., 2011), and therefore the impact of NT is pronounced (positive relation between NT-CT and annual mean temperature in this study).

The impact of NT was more significant in coarse- and medium-textured soils with 77% and 12% higher SOC stock compared to fine-textured soils over a 0–30 cm profile. Soils with higher clay content tend to have higher SOC content than soils with low clay content under similar land use and climatic conditions (Christensen, 2001; Milne and Heimsath, 2009). The impact diminished as the clay content increased beyond 20% and showed an overall negative relationship with the relative change in SOC under the no-till, supported by others (Huang et al., 2002; Liu et al., 2014). A slower biodegradation rate of organic matter in soils of high clay content could be a probable reason (Balesdent et al., 2000; Liu et al., 2014). Compared to conventional tillage, NT increases the stability of aggregates (Mondal et al., 2020; Mondal and Chakraborty, 2022), further reducing the turnover of soil organic matter. Coarse-textured soils have poor structural conditions, showing a more significant response to NT. Stabilization of SOC by promoting soil structure is more evident in medium-textured soils. However, we could not differentiate the effect of cropping systems in our study, although cereal-cereal rotation appeared to favour the accumulation of SOC in the surface layers, while the influence extended to greater depths with a legume in the cycle (Hernanz et al., 2002).

Retaining crop residues on the surface enhances substrate availability and microbial activity, resulting in a large amount of MBC in the 0–5 cm soil layer (Table 1). Others reported similar findings (e.g., Kaschuk et al., 2010; Zuber and Villamil, 2016; Fang et al., 2018). Soil aggregate-associated C increased in the upper layers, irrespective of size (Hontoria et al., 2016; Mondal et al., 2019).

We observe that NT duration is a dominant factor that moderates C accumulation. More significant changes were recorded in the subsurface layers with the increased duration of NT practice. Meta-regression showed an increase in the SOC stock with an increase in duration over a 0–30 cm soil profile. Others reported similar findings (Angers and Eriksen-Hamel, 2008; Liu et al., 2014; Han et al., 2016; Haddaway et al., 2017). However, the period of adoption of NT when SOC stocks reach a steady state varied among the studies (e.g., 11 yr, Hernanz et al., 2002; 15 yr, West and Post, 2002; 30 yr, Alvarez et a, 2005; 25–50 yr, Follett, 2001). The effect of temperate climate on the change in SOC stock increased with a longer duration, and so was the impact on the medium-textured soils.

The 0–30 cm soil profile may be taken as an optimum depth over which maximum change in SOC stock takes place. Considering ≤ 10 yr duration, our estimate is close to West and Post (2002) and Haddaway et al. (2017) but higher compared to Virto et al. (2012) and Meurer et al. (2018). Soil C sequestration must consider the net balance of all GHGs in a specific agroecosystem over a specified period (Bernoux et al., 2016; Lugato et al., 2018). With a minimum 10 yr duration, NT can add 0.664 Mg C ha^{-1} yr^{-1} (Table 2), which is very close to the recommendation to offset the global anthropogenic GHG emissions ('4 per mille'; Minasny et al., 2017). However, this change is improbable because only 9–15% of global arable land is currently under NT (Prestele et al., 2018). The current area estimate allows NT to offset a meager 1.1% global GHG emission. However, NT currently mitigates a substantial 6–17% emission from crops & livestock and can potentially increase mitigation potential to 20–58% (Fig. 5). This makes NT possible to push agriculture towards zero-emitter of GHGs, which is a more reasonable approach than mitigating global anthropogenic GHGs emissions.

Mitigation of atmospheric CO_2 increase through C sequestration in soils has been an object of widespread debate on its economical and practical feasibilities (Powlson et al., 2011; Sanderman et al., 2017; Van Groenigen et al., 2017; Poulton et al., 2018; Ranganathan et al., 2020). Although the C sink potential of the soils is estimated at 133 Pg C, $< 10\%$ of it can be filled up with best management practices (Sanderman et al., 2017) considering the biophysical potential of cropland and pasture for C sequestration (Lal, 2001; Smith et al., 2008), assuming a 20 yr of stability of C in soil (West et al., 2004; Eggleston et al., 2006). The mineralization of new organic matter added to soils is often not considered, which may require even, more significant amounts of C-addition to achieve the desirable sequestration (Berthelin et al., 2022). Farmers only sometimes have large amounts of organic residues to add to the soil yearly, even under the no-tillage practice, especially in tropical and subtropical regions. The stoichiometric constraint of a large increase in SOC has also been argued (Van Groenigen et al., 2017).

The potential benefits of no-tillage agriculture are well-documented, ranging from a substantial improvement in soil health (Mondal et al., 2020, 2022) to reduce annual fuel energy (Mileusnić et al., 2010) and labour costs (Pandit et al., 2010). Improving soil quality ensures higher yield stability and makes crop production resilient to climate change (Qiao et al., 2022). The effect of climate change, predominantly through increasing weather aberrations, makes the soil more vulnerable to sustaining its primary role in food security. No-till cultivation by arresting soil erosion through its ability to reduce runoff and infiltrate water during high rainfall (Williams et al., 2017) and by conserving and supplying soil water during prolonged dry periods (Ding et al., 2009) can significantly contribute to ensuring the food security under extreme weather conditions. It is wise now to change the perspective of looking at the soil functions that NT can support and improve, contrary to our current focus on the soils as a solution to offsetting global GHG emissions.

5. Limitations and sources of uncertainties

Reported soil depths were highly variable, making it challenging to reach a general agreement. For SOC stock calculation, in a few instances, data were not given for the entire depth (say 50 cm); in that case, the last depth was extrapolated. A few rainfall data and all temperature data were extracted from the “worldclim” database; therefore, these could be slightly different from the actual values. The number of paired data points varied in subgroups, which might impact the results. Our estimates of global C sequestration potential under NT may have uncertainties arising out of a poorly-defined framework of inclusion of NT farming. The potential area estimates may widely vary due to socio-economic, cultural, and institutional factors of NT adoption at local and regional scales.

6. Conclusions

The large increase in organic SOC concentration led to a significant increase in SOC stock in the top 0–5 or 0–10 cm soil layers. The 0–30 cm soil can be taken as an optimal profile depth to assess the impact and quantify C-sequestration under NT. An increase in SOC is essentially through an increase in labile C pools, which has limited sustenance but contributes largely to improving soil health and crop productivity. No cropping system or soil texture is preferred to facilitate SOC change under no-till, but tropical climates could accumulate more in the deeper layers. The contribution of NT in mitigating global GHG emissions is trivial, although its role in offsetting agricultural GHG emissions may be significant. We must emphasize restoring soil functions by adopting NT and research programmes guided by it and shift the current focus to NT’s contribution to mitigating GHGs emissions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2023.108498.

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